

## **Clouds and Water Vapor in the Climate System**

Summary of Research  
NASA Goddard Grant NAG5-8779  
August 1, 1999–February 28, 2002

Submitted to  
National Aeronautics and Space Administration  
from  
President and Fellows of Harvard College  
c/o Office for Sponsored Research  
Holyoke Center, Suite 727  
1350 Massachusetts Avenue  
Cambridge, Massachusetts 02138

James G. Anderson, Principal Investigator  
Division of Engineering and Applied Sciences  
Department of Earth and Planetary Sciences  
Department of Chemistry and Chemical Biology  
Harvard University  
12 Oxford Street  
Cambridge, MA 02138

May 30, 2002

## NASA Grant NAG5-8779, "Clouds and Water Vapor in the Climate System"

We review here the scientific progress that has emerged during the period August 1, 1999 through February 28, 2002, supported by NASA Grant NAG5-8779.

### Objective of the Research Funding:

Research supported under this grant was aimed at attacking unanswered scientific questions that lie at the intersection of radiation, dynamics, chemistry and climate. Considerable emphasis was placed on scientific collaboration and the innovative development of instruments required to address these issues. Specific questions include:

- *Water Vapor Distribution in the Tropical Troposphere:* An understanding of the mechanisms that dictate the distribution of water vapor in the middle-upper troposphere is essential for predicting the response of the tropics to increases in greenhouse gas loading. Is the distribution of water vapor controlled by simple assumptions regarding deep convection that sets the vertical moisture pattern followed by advection that establishes the horizontal distribution or does an increase in sea surface temperatures lead to a drying due to increased subsidence associated with increased convective mass flux? This research obtained data needed to define the water vapor distribution in the context of multiple tracer observations and improve retrievals of water vapor and cloud ice concentration using spectrally resolved radiance observations.
- *Atmospheric Radiation:* In the spectral region between 200 and 600 $\text{cm}^{-1}$  that encompasses the water vapor rotational and continuum structure where most of the radiative cooling of the upper troposphere occurs, there is a critical need to test radiative transfer calculations using accurate, spectrally resolved radiance observations of the cold atmosphere obtained simultaneously with *in situ* species concentrations. An associated area addresses the testing of upper-troposphere water retrievals from infrared sounders.
- *Thin Cirrus:* Cirrus clouds play a central role in the energy and water budgets of the tropical tropopause region. A central objective of this research was to test and improve the accuracy with which cirrus, and in particular subvisible cirrus, can be remotely sensed and mechanistically understood. Thin cirrus radiative properties were studied using a combination of *in situ* measurements and INTESA radiance/transmittance measurements such as the applicability of recent small-particle scattering algorithms over a wide wavelength range. Emphasis was placed on the ability to detect thin cirrus in the 10-12 micron window using up-welling radiances and then using these spectral scattering measurements to predict outgoing longwave radiation (OLR) when thin cirrus are present.
- *Stratosphere-Troposphere Exchange:* Assessment of our ability to predict the behavior of the atmosphere to changes in the boundary conditions defined by thermal, chemical or biological variables is sensitively related to the degree of our understanding of the fundamental mechanisms that control the exchange of material across the tropopause. The developing hypothesis that lower stratospheric water vapor concentrations result from upward advection of air with a mixing ratio characteristic of the zonal mean tropopause saturation mixing ratio.

must be directly and exhaustively tested. These unique measurements were carried out along trajectories that take vertical cuts through the lower stratosphere-upper troposphere as well as horizontal scans immediately above and below the tropopause.

- *Correlative Science with Satellite Observations:* Linking this research to the developing series of EOS observations is critical for scientific progress. Several avenues are immediately apparent. Spectroscopy of the atmosphere detailing the water vapor continuum at cold temperatures in the AIRS sounding channels in the 6 micron band as well as the 4.3 micron region of CO<sub>2</sub> are crucial. Development of a thin cirrus detection algorithm for the AIRS sounder that could also predict the (unmeasured by AIRS) spectral OLR that corresponds to these conditions is clearly of high priority as are retrievals of UTH that will be made to test AIRS retrieval methods. Coordination of campaign flights to overlap with EOS-AM satellite observations to test CO observations by MOPITT using both *in situ* measurements as well as INTESA solar transmittance observations will provide powerful constraints. Testing the upper tropospheric water observations obtained by AIRS using WB-57 *in situ* water vapor over a range of stair-step flight patterns coupled with INTESA observations of up-welling radiance will emerge as a central research topic.

Results from this research grant fall into three categories. The first category involves the development of instrumentation to dissect mechanisms controlling the chemical, dynamical and radiative structure of the upper troposphere and lower stratosphere with an emphasis on the tropics. The second category involves the integration of these instruments onto the WB-57 aircraft platform, with engineering test flights to verify the successful operation of these instruments from the tropospheric boundary layer to the lower stratosphere. The third category involves the deployment of the aircraft and instruments into the inner tropics to obtain vertical and horizontal soundings of the Tropical Transition Layer (TTL) in both convectively active and clear conditions. We report the results of this research in each category.

Category 1: Five instruments were developed for climate studies from the WB-57 aircraft. The first was an instrument designed for the *in situ* detection of tracers, isotopes and reactive intermediates using cavity ring down spectroscopy (CRDS). This method provides both extreme sensitivity and fast time response in a robust configuration for aircraft deployment. This is the first time the method has been used on an aircraft mission. The second instrument developed was designed to detect *in situ* the total mixing ratio of water (vapor, liquid and solid) with a time response of 10 seconds and an accuracy (absolute) of  $\pm 5\%$ . The third and fourth instruments were redesigned systems for the *in situ* detection of ozone and water vapor with a time response of 10 seconds and an accuracy of  $\pm 5\%$ . The fifth instrument was a Fourier Transform Interferometer designed to determine the absolute, spectrally resolved radiance throughout the thermal infrared to an accuracy of 0.1 K. All five of these instruments were developed for the WB-57 and flown successfully under this grant.

Category 2: These five instruments were delivered to Johnson Space Flight Center and integrated onto the aircraft in February 2001. All instruments performed superbly, meeting or exceeding their design specifications in flight.

Category 3: In August 2001, the WB-57 was deployed into the tropical eastern Pacific out of Costa Rica. Seven flights were executed during the two-week deployment and the scientific results were excellent. The TTL was scanned vertically forty times under a wide range of conditions from quiescent to highly convectively disturbed. High resolution *in situ* observations of O<sub>3</sub>, H<sub>2</sub>O and total water (along with pressure, temperature) in combination with observations of absolute, spectrally resolved radiance were obtained defining the role of convection and dehydration in the control of exchange between the troposphere and stratosphere. Post-flight calibrations have been completed and we are entering the data interpretation phase.

There are no inventions resulting from this funding.

A final report from our subcontractor at the University of Maryland is attached.

# Radiative Transfer in Clear Air and Cirrus Clouds in the Tropics

Subcontract on NASA grant NAG5-8779 to Harvard University

Sergio De Souza-Machado, L. Larrabee Strow,  
Howard Motteler and Scott Hannon  
Physics Department  
University of Maryland Baltimore County  
Baltimore, MD 21250 USA

## 1 Introduction

One of the motivating factors for the joint research involving UMBC and Harvard University was to detect the presence of high altitude thin tropical cirrus clouds. Data obtained using the Harvard University interferometer would need to be compared to radiative transfer simulations where parameters such as mean particle size, ice path, cloud height and thickness would need to be retrieved in some fashion.

While there exist some well known scattering algorithms such as *DISORT* and *RTSPEC*, these codes depend on using clear sky optical depths and cloud scattering parameters generated by external codes. UMBC had written kCARTA, a clear sky radiative transfer code that was self contained in the sense that it could rapidly compute clear sky optical depths and then do radiative transfer through a clear atmosphere. In addition UMBC has vast experience in developing Fast Forward models for instruments such as the *HIS* and *AERI* interferometers.

To support Harvard University, UMBC proposed to interface scattering algorithms with kCARTA, and to develop a rapid model. While assessing the relative merits of *DISORT* and *RTSPEC* for this purpose, we developed our own *TWOSTREAM* scattering algorithm. This algorithm could be easily modified to be used as a single scattering layer in a Fast Model as well. All three scattering codes have now been interfaced with kCARTA.

## 2 Clear Sky Optical Depth computations

kCARTA uses a set of precompressed tables to compute the contribution of each individual gas to an infrared spectrum. These precompressed tables contain optical depths as a function of pressure and temperature. With the layer pressures spanning 1100 mb down to 0.005 mb, and layer temperatures spanning approximately

---

180 K to 350 K, the tables extend over a wide enough range to cover any arbitrary but realistic Earth profile.

The optical depths are stored at a  $0.0025\text{ cm}^{-1}$  spacing, enough to resolve high altitude voigt lines in the infrared. Covering the infrared region between  $605$  and  $2830\text{ cm}^{-1}$ , the optical depths are computed using our custom UMBC-LBL code, using line parameters from the HITRAN98 database, with Toth water lines included. In addition, UMBC's latest estimates of linemixing parameters are used for the CO<sub>2</sub> lineshapes in the important temperature sounding  $15$  and  $4\text{ }\mu\text{m}$  regions. Having generated the "monochromatic" database, singular value decomposition (SVD) is used to compress the database to a manageable size, while still maintaining an accuracy so that radiative transfer errors between ground and TOA are at or below errors due to spectroscopy.

As the INTESA campaign would be measuring radiances in the Far InfraRed  $400\text{ cm}^{-1}$  region, UMBC would need to extend the wavenumber spread of the database. In addition, the doppler widths scale with wavenumber, thereby requiring a finer wavenumber spacing in the Far Infrared. kCARTA has now been rewritten so that it can easily handle this extended database at a finer point spacing, as well as the original database at the  $0.0025\text{ cm}^{-1}$  spacing.

### 3 Clear Sky Radiance computations

Using the compressed database, the optical depth for an actual profile is easily computed by first interpolating the database to the correct temperature and layer pressure for each gas, and then uncompressing. This makes kCARTA especially fast : for a 100 layer  $25\text{ cm}^{-1}$  chunk at a point spacing of  $0.0025\text{ cm}^{-1}$ , the cumulative spectra for all gases are typically generated in less than 5 seconds on an Intel 1 GHz machine.

Having computed the cumulative optical depths for the atmospheric layers, kCARTA can now proceed to do a clear sky radiance computation. Using information such as surface temperature, pressure and emissivity, satellite view angle, observation pressure and direction that the user has specified in a namelist file, the code can compute clear sky radiances for either an uplook or downlook instrument at any angle (although it should not be used for limb viewing).

For a downlook instrument, kCARTA computes the background thermal contribution using an accurate diffusivity approximation; at each layer below a set (though spectrally varying) height, an optimum angle is used in the diffusivity approximation, based on the layer-to-ground optical depth. This makes kCARTA radiance computations fast and accurate. In addition to the time taken to compute cumulative optical depths, radiative transfer through a  $25\text{ cm}^{-1}$  chunk would add

---

on an additional 5 seconds to the run time on the same 1 GHz machine. This means that kCARTA can compute an entire *monochromatic* IR spectrum ( $605\text{ cm}^{-1}$  to  $2830\text{ cm}^{-1}$ ) in less than 15 minutes.

## 4 Cloudy Sky Optical Depth computations

kCARTA can also make use of scattering parameters such as extinction optical depths, single scattering albedo and asymmetry. At present these parameters need to be included in the format used by Frank Evans' *RTSPEC* code, which uses information from Evans' *sscatmie* code. While this scattering code outputs parameters using Mie (spherical particle) scattering theory, the format is general enough to allow inclusion of the same parameters for arbitrary scattering particle shape, from any other relevant code. We have already run a slightly modified version of the *sscatmie* code to store water, cirrus and aerosol scattering parameters from 405 cm to 2905 cm, for various mean particle sizes and layer temperatures. These tables can be easily read in by kCARTA when needed.

## 5 Cloudy Sky Radiance computations

kCARTA has now been interfaced to two well known and tested scattering packages, *DISORT* and *RTSPEC*. The first of these, *DISORT*, can include the effects of solar beam scattering, but due to extensive matrix computations, is slow. Using *DISORT* at a monochromatic spacing can increase the kCARTA runtime by orders of magnitude, compared to a clear sky computation; the best remedy was to compute radiative transfer at every 400 or so points and interpolate the results to the  $0.0025\text{ cm}^{-1}$  spacing; even this could increase the kCARTA runtime by about a factor of two or three, compared to a clear sky computation.

*RTSPEC* is very fast, but currently does not allow the user to include a solar beam. To combine speed and beam scattering, we developed and included our *TWOSTREAM* code into kCARTA. Cloudy sky computations using either *RTSPEC* or *TWOSTREAM* code would increase the kCARTA runtime by less than 20% over a clear sky computation.

Using any of these three scattering packages, kCARTA can handle onelayer or multilayer cloud(s), again for either uplooking or downlooking instruments. Concentrating on the window regions, we have extensively tested *TWOSTREAM*, *RTSPEC* and *DISORT* against each other. Typically, for a downlook instrument, the brightness temperature differences between the three codes is less than about 1 K in the long wave window region. With the sun "on", the differences between *TWOSTREAM*

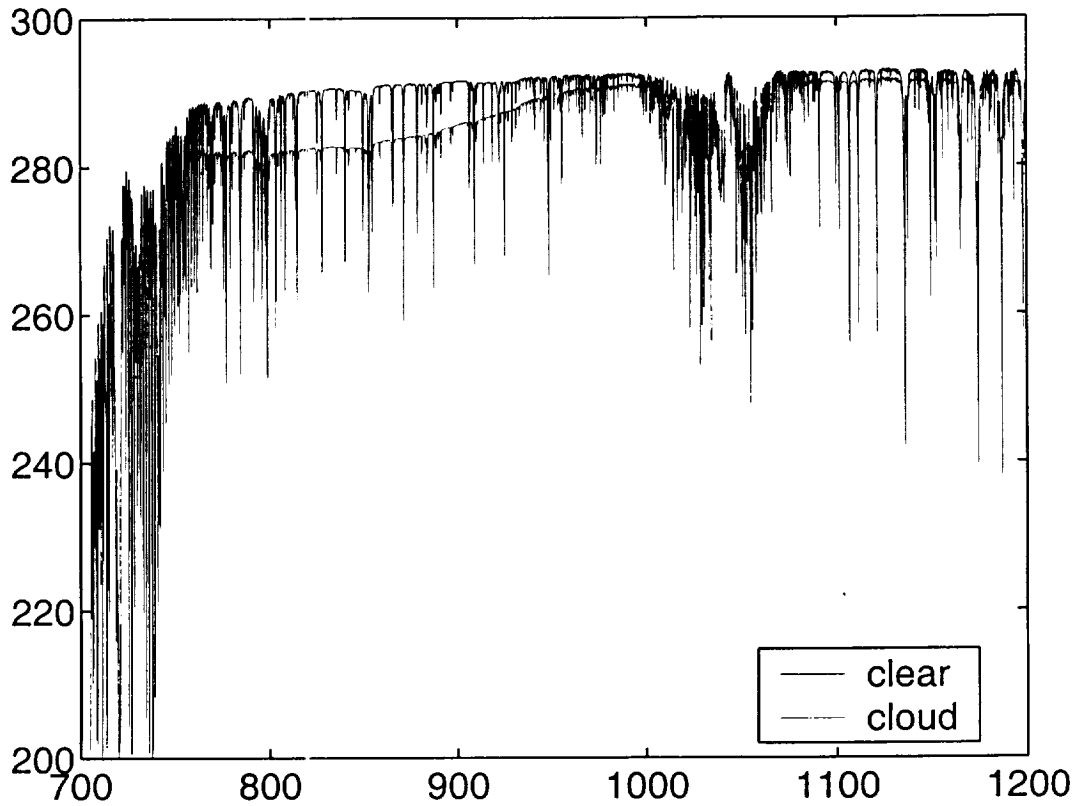


Figure 1: Clear(blue) and Cloudy(red) radiances in the 10-12  $\mu m$  window region. X-axis is wavenumber, Y-axis is brightness temperature in K.

and *DISORT* is typically less than 3 K in the short wave (solar) region. Figure 1 shows a typical simulation for a downlooking instrument. The blue is the simulated radiance for a clear look, while the red is a similar plot for a 11 km high cirrus cloud, with mean particle size 2  $\mu m$  and ice path of 0.4  $g/m^2$ .

When looking at the sample results of kCARTA with scattering, it is clear that there are cirrus spectral signatures in the 10-12  $\mu m$  range. These signatures change as the mean particle size and ice path change, meaning it should be possible to retrieve these two parameters, and possibly others such as cloud base and thickness.



---

## 6 Additional packages

kCARTA is also the science basis for NASA's AIRS instrument, due to be launched on board the AQUA platform in April 2002. kCARTA has been interfaced to a *RTP* file format, which allow us to easily store multiple profile and radiance information. The profiles in this file format can be sent through our *KLAYERS* code, so that a levels profile is changed to a layers averaged profile, that can be used by kCARTA. The output from kCARTA is binary f77 files; we supply f77 and Matlab readers that can be used to postprocess the output.

## 7 Conclusion

To help support Harvard University, UMBC has extensively developed the kCARTA code during the past two years. It can easily handle an extended database so that the Far IR is covered, and now includes three scattering packages. In addition, a simple one layer version of the *TWOSTREAM* algorithm is ready for use in a Fast Forward Model.